Curbing the U.S. carbon deficit

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The U.S. emitted ≈1.58 petagrams (Pg) of fossil fuel carbon in 2001, approximately one-quarter of global CO_2 production. With climate change increasingly likely, strategies to reduce carbon emissions and stabilize climate are needed, including greater energy efficiency, renewable energy sources, geoengineering, decarbonization, and geological and biological sequestration. Two of the most commonly proposed biological strategies are restoring organic carbon in agricultural soils and using plantations to sequester carbon in soils and wood. Here, we compare scenarios of land-based sequestration to emissions reductions arising from increased fuel efficiency in transportation, targeting ways to reduce net U.S. emissions by 10% (≈0.16 Pg of carbon per year). Based on mean sequestration rates, converting all U.S. croplands to no-till agriculture or retiring them completely could sequester ≈0.059 Pg of carbon per year for several decades. Summary data across a range of plantations reveal an average rate of carbon storage an order of magnitude larger than in agricultural soils; in consequence, one-third of U.S. croplands or 44 million hectares would be needed for plantations to reach the target of ≈0.16 Pg of carbon per year. For fossil fuel reductions, cars and light trucks generated ≈0.31 Pg of carbon in U.S. emissions in 2001. To reduce net emissions by 0.16 Pg of carbon per year, a doubling of fuel efficiency for cars and light trucks is needed, a change feasible with current technology. Issues of permanence, leakage, and economic potentials are discussed briefly, as is the recognition that such scenarios are only a first step in addressing total U.S. emissions.

agriculture and plantations | carbon sequestration | fossil fuel emissions | leakage and permanence | soil organic carbon

As a nation, the U.S. emitted ≈1.58 petagrams (Pg) of fossil fuel carbon in 2001 (1), approximately one-quarter of the global production of CO_2. With climate change increasingly likely (2), strategies to reduce carbon emissions and stabilize climate are needed (3, 4). Such strategies include increased energy efficiency, renewable energy sources, geoengineering, decarbonization, and geological and biological sequestration (3, 4). Two of the most commonly proposed biological strategies are restoring organic carbon in agricultural soils and using plantations to sequester carbon in soils and wood (3, 5–10). Here, we compare scenarios of land-based sequestration in agricultural soils and forest plantations to emissions reductions that could arise from increased fuel efficiency in transportation. As an initial target, we examine ways to reduce net emissions in the U.S. by 10% or ≈0.16 Pg of carbon per year.

To Swards from Plowshares

Land-based sequestration in agricultural soils restores all or part of the soil organic carbon (SOC) lost with plowing and intensive agriculture (6–10). Methods for restoring SOC in agricultural soils include no-till management and cropland retirement programs such as the Conservation Reserve Program (CRP) of the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service. Established in 1985 as a tool to reduce erosion from agricultural lands, the CRP pays farmers to replace row crops with grasses and other perennial plants. As of January 2003, landowners had enrolled ≈14 million hectares (ha) of agricultural lands in the CRP (11).

Potential carbon storage in U.S. agricultural soils can be estimated by combining observed sequestration rates through the CRP and no-till agriculture with the extent of agricultural lands in the U.S. Recent reviews of >100 observations concluded that SOC increased ≈450 kg of carbon per ha per year after croplands converted to pastures or no-till management (9, 10).[§] Maximum rates of storage peaked 5–10 years after conversion and slowed considerably within two decades (10). The U.S. also had an estimated 132 million ha of cropland in production in 2001 (11).[¶] In consequence, if the U.S. converted its croplands entirely to no-till agriculture or, less likely, retired them all through the CRP, potential sequestration rates of 0.059 Pg of carbon per year might be possible for several decades (ref. 9 and Fig. 1).[§] This upper limit for sequestration is slightly more than one-third of the target of 0.16 Pg of carbon per year chosen here but still <4% of total U.S. fossil fuel emissions.

Forest plantations grown on former agricultural lands have greater sequestration potentials because carbon can be stored both in the soil and as wood. Summary data across a range of plantations reveal an average rate of carbon storage of 3,600 kg of carbon per ha per year (12),[‖] an order of magnitude larger than that in agricultural soils (9, 10).[§] Based on this rate, 44 million ha or one-third of all U.S. croplands would be needed for growing trees to reach the target of ≈0.16 Pg of carbon per year.

Although plantations provide greater rates of carbon storage than soils alone, the uncertainties may be larger. Sequestration rates somewhat higher than 3,600 kg of carbon per ha per year are likely possible in some locations and in the short term (13). However, none of these estimates takes into account the carbon

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Abbreviations: Pg, petagram; SOC, soil organic carbon; ha, hectare; CRP, Conservation Reserve Program; USDA, U.S. Department of Agriculture; mpg, miles per gallon.

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[§] The average estimate for soil carbon storage after a shift from agriculture to pasture is 332 kg of carbon per ha per year (based on 39 observations in ref. 9). The estimate for the change from conventional tillage to no-till agriculture in ref. 10 is based on 67 long-term agricultural experiments and was slightly higher, 570 kg of carbon per ha per year, but excludes wheat fallow systems where no significant increase in soil carbon was observed. Additional net savings of ≈30 kg of carbon per ha per year in no-till versus conventional tillage may be attributable to reduced emissions from tillage itself. For our analysis, we use the mean of the above estimates, 450 kg of carbon per ha per year. This estimate of carbon storage is then combined with the estimated cropland area in the U.S. (132 million ha; ref. 11) to place an upper limit on SOC storage in agricultural lands (0.059 Pg of carbon per year). The estimate is consistent with the lower range in potential sequestration presented by Lal *et al.* (7) for U.S. croplands: ≈3,000 million metric tons of carbon over a 25- to 50-year period (0.059 Pg of carbon year × 50 years = 2.95 Pg of carbon or 2,950 million metric tons of carbon).

[¶] The USDA estimate of U.S. croplands (132 million ha) is approximately one-third of the "farmland" estimate of 380 million ha from National Agricultural Statistics Service estimates. However, the latter also includes acreage for pasture lands, grazing lands, and woodlands and wastelands that are part of farmers' total operations.

[‖] The article in ref. 12 presented data from a range of pine plantations in their table 5. We calculated the average carbon gains based on age of the stands and the carbon gains above and below ground (3,640 kg of carbon per ha per year). Estimates of the amount of soil carbon alone stored after forestation of agricultural lands are similar to summary values for shifts from agriculture to pasture (338 and 332 kg of carbon per ha per year, respectively; ref 9).[§]

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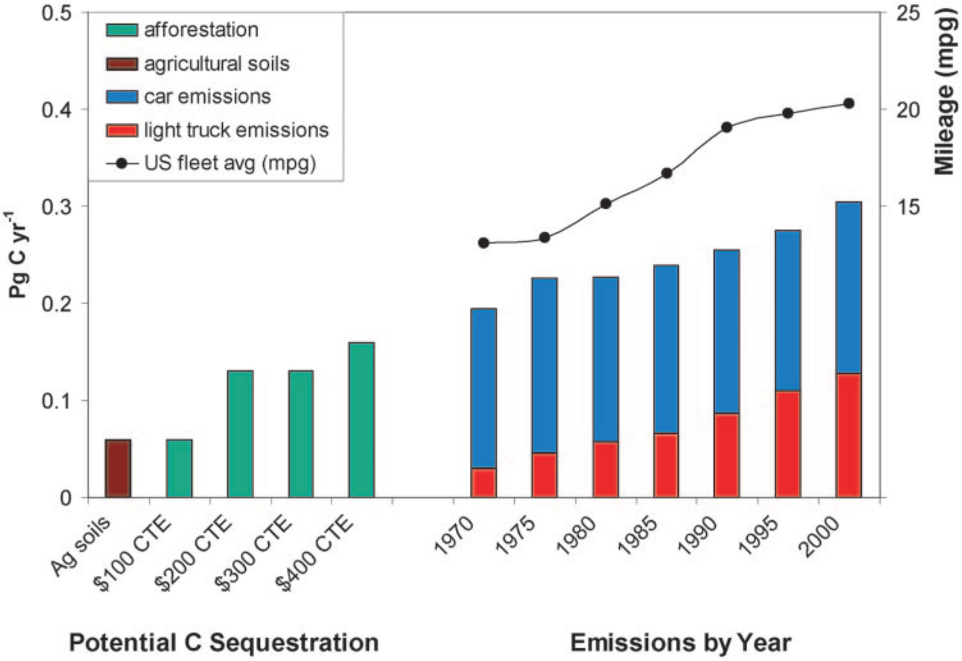

Fig. 1. Carbon emissions in Pg of carbon per year from cars and light trucks (blue and red bars) in the U.S. from 1970 to 2000 (ref. 19, and http://bioenergy.ornl.gov/papers/misc/energy_conv.html), maximum potential carbon storage estimated for agricultural soils in the U.S. (brown bars; refs. 9–11),[§] potential carbon sequestration for afforestation at carbon prices of $100–400 per metric ton carbon equivalents (green bars; ref. 17), and average U.S. fleet mileage for cars and light trucks combined (black line; calculated from data in ref. 19).[§]

costs of site preparation and planting, potential carbon losses from disturbance [e.g., storms, pests, and fires (14)], post-harvest carbon losses in timber use [e.g., sawmills or landfills (15)], and additional biogeochemical changes that might occur [e.g., decreased water yields (16)]. Because increases in plantation area do not automatically increase demand for wood products, some of the plantation carbon will likely return to the atmosphere after harvesting, if long-term uses for the wood are not found. Thus, the net storage will be lower than the technical potential and will reflect the proportion of harvested carbon that returns to the atmosphere and the regional chronology of planting and harvesting. A national policy promoting afforestation can store considerable carbon for decades, but the amount stored, the economic subsidies needed, and the environmental changes that would result require careful evaluation.

Issues of permanence and leakage (17, 18), activities shifted to locations outside of a sequestration program that counteract some of its benefits, are important for all analyses of carbon sequestration and management. Carbon stored as soil organic matter or wood must be protected from plowing, fire, storm damage, and/or decomposition to keep the carbon from returning to the atmosphere. An alternative approach that acknowledges these uncertainties is carbon "rental" payments (18), whereby farmers contract to store carbon for set periods of time only. Such payments explicitly acknowledge the uncertain permanence of biologically sequestered carbon.

Car Talk

The transportation sector provides another opportunity to reduce carbon emissions to the atmosphere. Gasoline and related fuels comprise 28% of total energy use in the U.S. (19),[**] mostly in passenger cars and light trucks. The category of "other two-axle four-tire vehicles" in the Bureau of Transportation Statistics includes light trucks, vans, and sport utility vehicles (SUVs) but does not include the heaviest SUVs. Cars and light trucks used 73 and 53 billion U.S. gallons of fuel, respectively, in 2001 (19). After converting fuel totals to carbon equivalents (the conversion factor used here is 2.42 kg of carbon per U.S. gallon of gasoline) (http://bioenergy.ornl.gov/papers/misc/energy_conv.html), these vehicle groups generated ≈0.31 Pg of carbon in U.S. fossil fuel emissions that year.

To reduce net emissions by 0.16 Pg of carbon per year, a doubling of fuel efficiency for cars and light trucks is therefore needed (Fig. 1), a change feasible with current technology (3). Fleet mileages in the U.S. for the two groups in 2001 were 22.1 and 17.6 miles per gallon (mpg), respectively (19). Newer vehicles in 2001 were substantially better: 28.6 mpg for cars and 20.9 mpg for light trucks (19). Although improvements in mileage will likely occur as newer vehicles comprise a greater proportion of the U.S. fleet, some of these gains are being offset by the increasing proportion of less-efficient light trucks in the U.S. (Fig. 1).

Far greater efficiencies are already available from hybrid electric vehicles (HEVs) and additionally from advanced diesel engines and lightweight construction materials. More than 100,000 HEVs with mileage ≈50 mpg (3) have been sold in North America to date. A policy to promote hybrid technology in new cars and light trucks would go a long way to doubling fuel efficiency to >40 mpg (Fig. 1). Providing economic incentives for high-mileage vehicles could reduce oil imports and would not require cultural changes such as driving fewer miles or pursuing mass transit, two other useful options.

[**] Table 4-2 in ref. 19 provides data for U.S. energy consumption from primary sources and the proportion attributable to transportation (28.1%). Table 4-5 provides data for total fuel consumption; passenger cars consumed 73.452 billion U.S. gallons and "other two-axle, four-tire vehicles" consumed 53.294 billion U.S. gallons in 2001. Table 4-23 gives the average fuel efficiency for the current fleet of cars and light trucks (22.1 and 17.6 mpg, respectively) and for new vehicles (28.6 and 20.9 mpg, respectively).

Just as with biological sequestration, permanence and leakage need to be acknowledged in improved fuel efficiency. Doubling the fuel efficiency of passenger cars and trucks will only cut vehicle emissions in half if the number of miles driven does not increase. Also, there is no guarantee that improvements in fuel efficiency would be permanent. However, unlike biological sequestration, where a fire or plantation harvest could liberate carbon stored over many years, the carbon emissions saved by improved fuel efficiency would not return to the atmosphere if mileage rates increased at a later date.

Hybrid Solutions

Reducing net carbon emissions can best be accomplished with multiple strategies (3). Land-based sequestration has an important role to play in this effort, but large land areas are needed to have a sustained effect. Peak rates of carbon storage in agricultural soils are typically maintained for a decade or two (10). Farmlands enrolled in the CRP currently store ≈0.005 Pg of carbon per year compared with U.S. fossil fuel emissions of 1.58 Pg of carbon per year. The cropland area managed for carbon storage will need to increase by an order of magnitude to approach the technical potential of ≈0.059 Pg of carbon per year estimated here.

Policy changes promoting carbon storage on land will have additional environmental costs and benefits (17), some predictable and some unforeseen. Potential benefits include reduced erosion and pollution from phosphorus and nitrogen runoff and improved wildlife habitat; potential costs include decreased food production in the U.S., increased food prices, and decreased agricultural exports, if large areas of farmland are taken out of production (17). In addition to evaluating the full benefits and costs of these policies, economic potentials also should be considered in making realistic projections of carbon storage. Recent economic models for the U.S. agriculture and forestry sectors suggest that carbon prices would need to be ≈$125–400 per metric ton of carbon equivalents for potential sequestration rates in plantations to approach 0.16 Pg of carbon per year (17, 18).

All of the approaches analyzed here, combined with renewable energy sources, decarbonization, geological sequestration, and other technologies (3), will be needed to balance the U.S. carbon deficit. Scenarios for offsetting 1/10th of U.S. fossil fuel emissions as described above show the scale and scope of changes that are needed; they also highlight how far the U.S. is from addressing its total emissions of 1.6 Pg of carbon per year. Reducing fossil fuel emissions directly will be needed to approach that goal. As one of many opportunities, hybrid gas-electric cars are already widely available. A doubling in fuel efficiency through hybrid technology, advanced diesel engines, and lightweight materials could precede a transition to hydrogen vehicles, which themselves require fossil fuels or other sources of energy to generate the hydrogen (20). Coupled with changes in the way that agricultural lands are managed, doubling the fuel efficiency of our nation's vehicles seems a logical first step in balancing the carbon budget.

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